Chapter 4

Power AC Transmission Lines

The submarine power AC cables have an important role in offshore wind energy. Furthermore, the submarine cables are the main difference between the offshore wind farms transmission system and onshore wind farms transmission system.

Therefore, a proper submarine cable model is crucial to perform accurate evaluations of the offshore wind farms collector and transmission systems. So, in the present chapter the different options to model a submarine cable are evaluated and their accuracy is discussed.

Then based on an accurate and validated submarine cable model, an analysis about the reactive power management in submarine power transmission lines is carried out. Thus, taken into account active power losses, the reactive power generated in the transmission system and the voltage drop for three different reactive power management options, a reactive power compensation option is proposed.

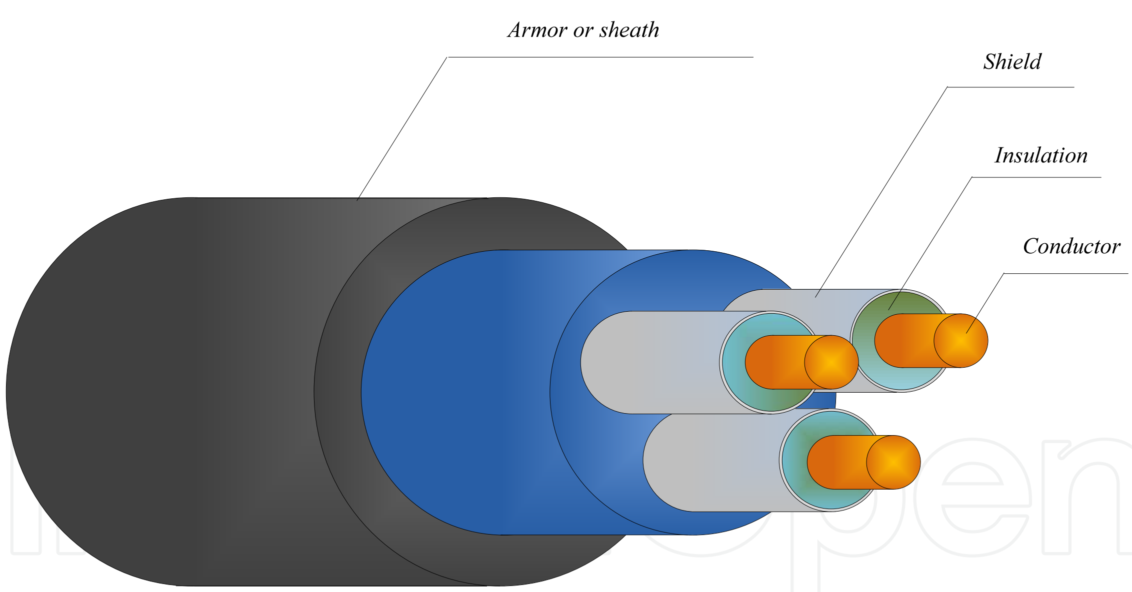


Figure 4.1 Generic representation of a electric power cable.

4.1 Basic components of electric power cables

The purpose of a power cable is to carry electricity safely from the power source to different loads. In order to accomplish this goal, the cable is made up with some components or parts. Figure 4.1 shows a description of the cable components, which are:

Conductor: The conductor is referred to the part or parts of the cable which carry the electric power. Electric cables can be made up by one conductor (mono-phase cables), three (three-phase cables), four, etc.

Insulation: Dielectric material layer with the purpose of insulate conductors of different phases or between phases and ground.

Shield: metal coating, which covers the entire length of the cable. It is used to confine the electric field inside the cable and distribute uniformly this field.

Armor or sheath: Layer of heavy duty material used to protect the components of the cable for the external environment.

4.1.1 Conductor

Some materials, especially metals, have huge numbers of electrons that can move through the material freely. These materials have the capability to carry electricity from one object to another and are called conductors. Thus, conductor is called to the part or parts of the cable which carry electric power.

The conductor may be solid or made up with various strands twisted together. The strand can be concentric, compressed, compacted, segmental, or annular to achieve desired properties of flexibility, diameter, and current density.

The choice of the material as a conductor depends on: its electrical characteristics (capability to carry electricity), mechanical characteristics (resistance to wear, malleability), the specific use of the conductor and its cost.

The classification of electric conductors depends on the way the conductor is made up. As a result, the conductors can be classified as [42]:

4.1.1.1 Classification by construction characteristics

Solid conductor: Conductor made up with only one conductor strand.

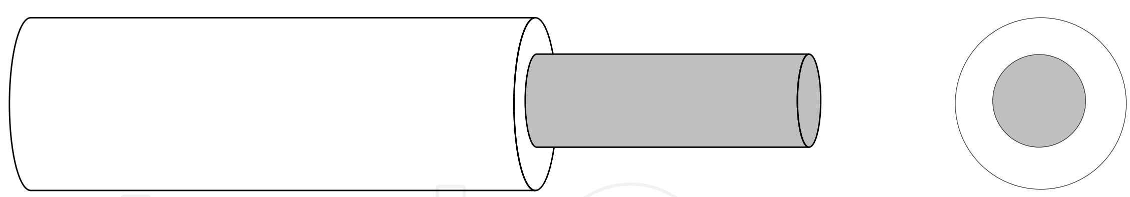


Figure 4.2 Conductor made up with Only one conductor strand.

Strand conductor: Conductor made up with several low section strands twisted together. This kind of conductor has bigger flexibility than solid conductor.

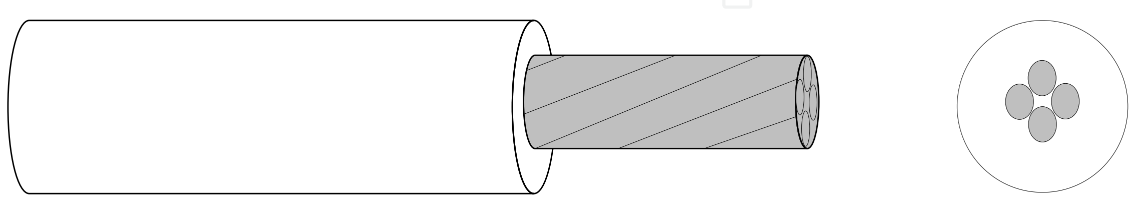


Figure 4.3 Conductor made up with several low section strands twisted together.

4.1.1.2 Classification by the number of conductors

Mono-conductor: Conductor with only one conductive element, with insulation and with or without sheath.

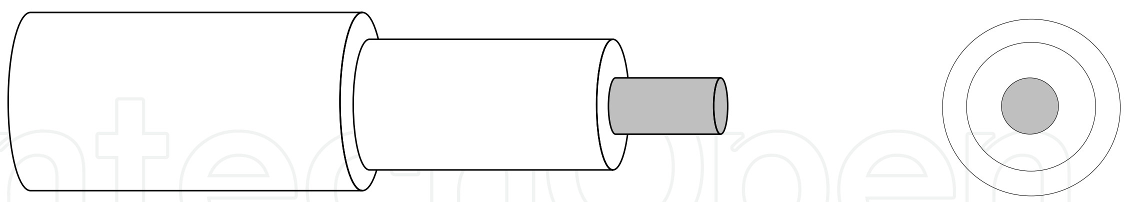


Figure 4.4 Conductor with Only one conductive element.

Multiple-conductor: Conductor with two or more conductive elements, with insulation and with one or more sheaths.

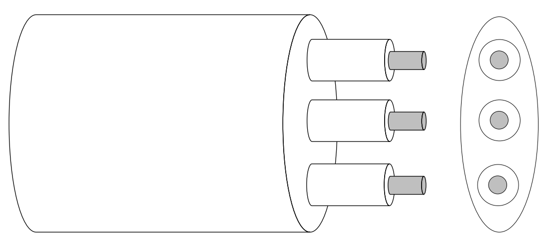


Figure 4.5 Conductor with multiple conductive elements.

4.1.2 Insulation

The purpose of the insulation is to prevent the electricity flow through it. So the insulation is used to avoid the conductor get in touch with people, other conductors with different voltages, objects, artifacts or other items.

4.1.2.1 Air insulated conductors

A metallic conductor suspended from insulating supports, surrounded by air, and carrying electric power may be considered as the simplest case of an insulated conductor [42].

Air is not a very good insulating material since it has lower voltage breakdown strength than many other insulating materials, but it is low in cost if space is not a constraint. On the contrary, if the space is a constraint, the air is replaced as insulation material for another material with higher voltage breakdown strength [42].

The same occurs in environments where isolation by air is not possible like submarine cables. In this case neither is possible isolation by sea water, since it is not an insulating material.

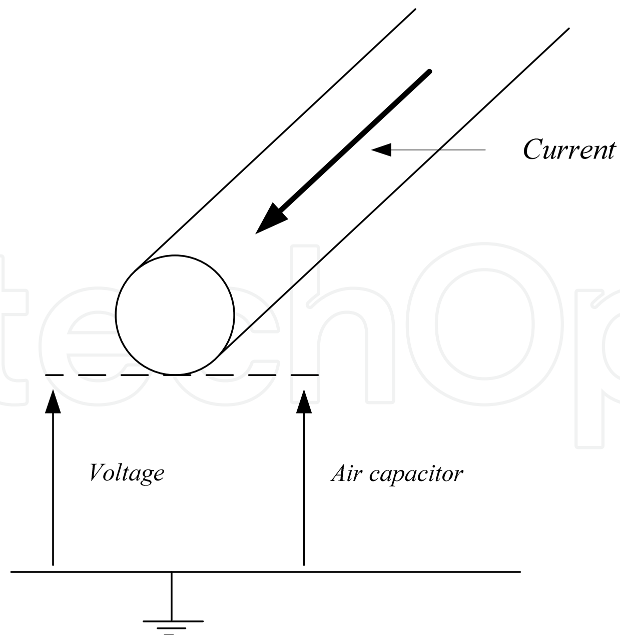


Figure 4.6 Air insulated conductor.

4.1.2.2 Insulation by covering the conductor with a dielectric material

In this type of insulation, the conductor is covered by an insulating material with high voltage breakdown strength (a dielectric), usually a polymer.

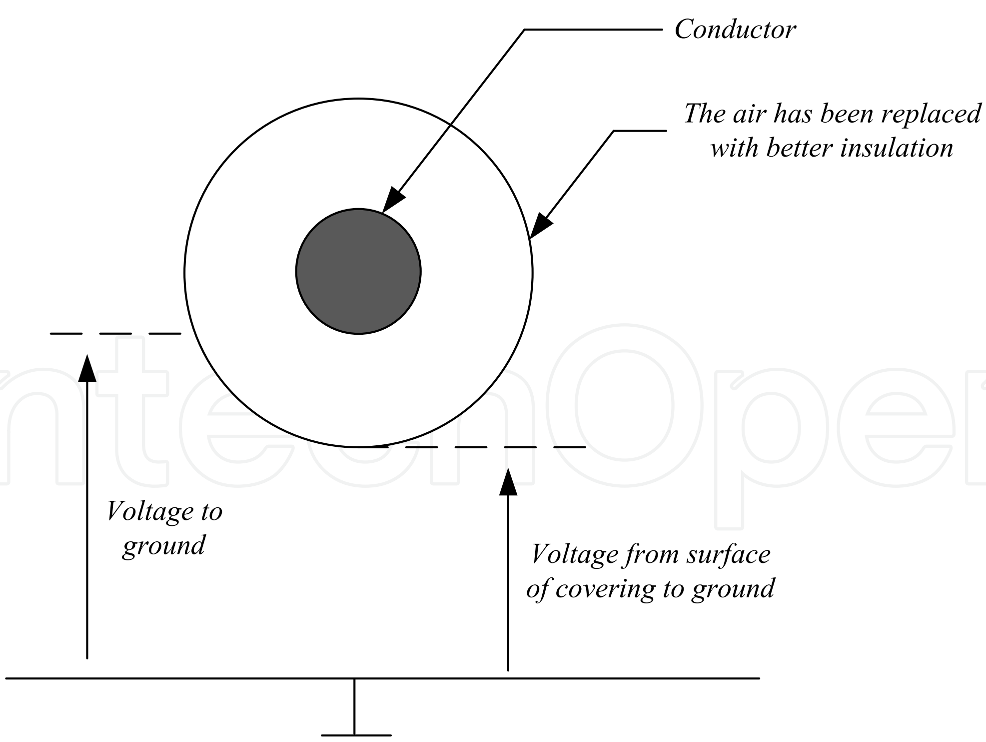


Figure 4.7 Insulation by covering the conductor with a dielectric material.

If the metallic conductor is covered with an insulating material, transmission lines can be placed close to ground or touching the ground. But in this cases when the ground plane is brought close or touches the covering, the electric field lines become increasingly distorted.

Considering the equipotential lines of the electric field, these are bended due to the potential difference on the covering surface. As shown in Figure 4.8.

At low voltages, the effect is negligible. As the voltage increases, the point is reached where the potential gradients are enough to cause current to flow across the surface of the covering. This is commonly known as "tracking." Even though the currents are small, the high surface resistance causes heating to take place which ultimately damages the covering. If this condition is allowed to continue, eventually the erosion may progress to failure [42].

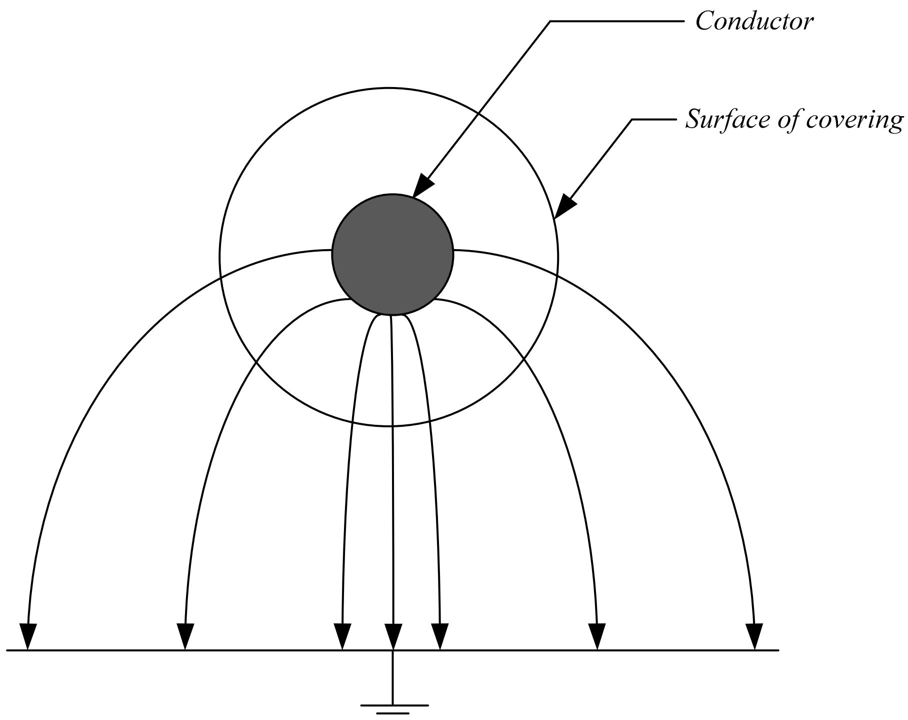


Figure 4.8 Equipotential lines of the conductor's electric field when the transmission line is close to the ground.

Therefore, high voltage power cables close to ground, like submarine cables, are provided with a shield to avoid this effect.

4.1.3 The insulation shield

The shield is a metallic coating over the insulation and connected to ground. The purpose of the shield is to create an equipotential surface concentric with the conductor to avoid the bending of the electric field lines.

The shield is also used to avoid the effects of external electric fields on the cable and as a protection for worker staff, through the effective connection to ground. The main reasons to use a shield are:

- To confine the electric field inside the cable between the conductor and the shield.
- To make equal the efforts inside the insulation, minimizing partial electric discharges

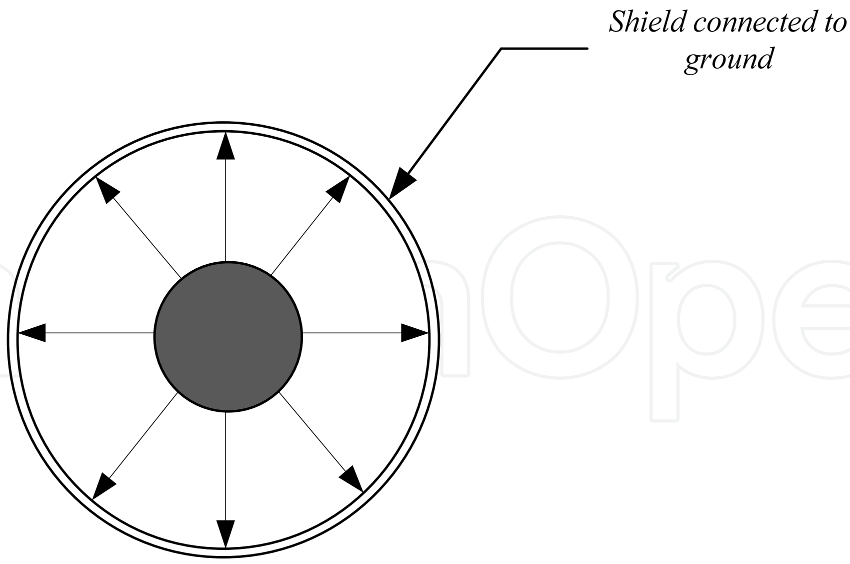


Figure 4.9 Equipotential lines of the conductor's electric field when the transmission line is provided with a shield.

- To protect the cable from induction voltages.
- To avoid electromagnetic or electrostatic interferences.

4.1.4 Armor or sheath

The purpose of this part of the cable is to protect the integrity of the insulation and the conductor from any mechanical damage such as scrapes, bumps, etc.

If mechanical protections are made by steel, brass or other resistant material, this mechanical protection is called as "armor." The "armor" can be composed by strips, strands or plaited strands.

The armor has especial importance in submarine cables, due to this type of cables are under water and the armor provides mechanical protection against to submarine water currents. Therefore, often submarine cables have an armor made up with a crown of steel strands in order to achieve a good mechanical protection [43].

4.2 Power transmission line modeling

4.2.1 Power transmission lines electric representation

A power transmission line presents several phenomena. First of all, the conductor of the cable used in power transmission lines has a small resistivity. Resistivity is the scalar property of an electric circuit which determines, for a given current, the rate of which electric energy is converted into heat or radiant energy. The resistivity of a specific cable is given by equation (18).

$$R = \frac{l}{\sigma \cdot A_c} \qquad \text{(ohm)} \tag{18}$$

Where: 'l' is the length of the cable, σ is the conductivity of the cable and A_c is the conductor area of the cable.

When an electric current flows through a conductor generates a magnetic field around it, which in turn induces an electric field. This field generates a current in the conductor in opposite direction of the original current. This effect is called self-inductance and can be described as [44]:

$$L = \frac{\mu_0}{8\pi} + \frac{\mu_0}{2\pi}\ln\left(\frac{b}{a}\right) \qquad \left(H/_{m}\right) \tag{19}$$

$$L = 0.5 + 0.2\ln\left(\frac{b}{a}\right) \qquad \left(mH/_{Km}\right) \tag{20}$$

Where: μ_o is the magnetic constant or the permeability of the free space and (a, b) are the radius of conductor cylinders (see Figure 4.10).

In case of cables with more than one wire or conducting element, besides the self inductance of each wire, must be also considered the electric field created in other wires. Consequently, the inductance of a multi-conductor cable mainly depends on the thickness of the insulation over the conductors.

Power transmission lines with triangular spatial disposition of the conductors, i.e. with the same separation between the three conductors present a self-inductance given by (21) [45]:

$$L = 0.05 + 0.2\ln\left(\frac{D}{a}\right) \qquad \left(mH/_{Km}\right) \tag{21}$$

Where: D is the distance between conductors and a is the conductor radius

It is important to highlight that the equations are for power lines with triangular spatial disposition. If the spatial disposition is with conductors in line, the value of the self-inductance is altered.

Another effect to be considered to represent a cable is the capacity of the line to ground (which is represented by the capacitor C). The voltage difference from the conductor to ground causes this effect.

In the cases of cables with insulation and placed close to the ground (like underground or subsea cables), they have to be provided with a shield. Thus, this capacity depends on the dielectric (insulation). Due to the fact that this capacitor represents the capacitive behavior performed between the conductor and the shield (a conductor connected to ground). In the most generic case is calculated by the equation (22).

$$C = \frac{Qe1}{V1 - V2} = \frac{Qe2}{V2 - V1} \qquad \text{(F)} \tag{22}$$

Where: *C* is the capacity of the cable, *V1* is the voltage of the conductor 1, *V2* is the voltage of the conductor 2, *Qe1* is the electric charge stored in the conductor 1 and *Qe2* is the electric charge stored in the conductor 2.

Simplifying the cable as a cylindrical conductor of radius "*a*" and a cylindrical surface coaxial with the first of radius "*b*" (*a* <*b*), where the space between them is filled with a dielectric material, Figure 4.10

It is possible to make the assumption that "*a*" and "*b*" (cable cross section) are very small in comparison with length (*l*) of the conductor cylinders (cable). As a result, the length of conductor cylinders (cable) can be considered as infinite, i.e. an ideal cylindrical capacitor. Where its capacity is given by equations (23) and (24) [46]:

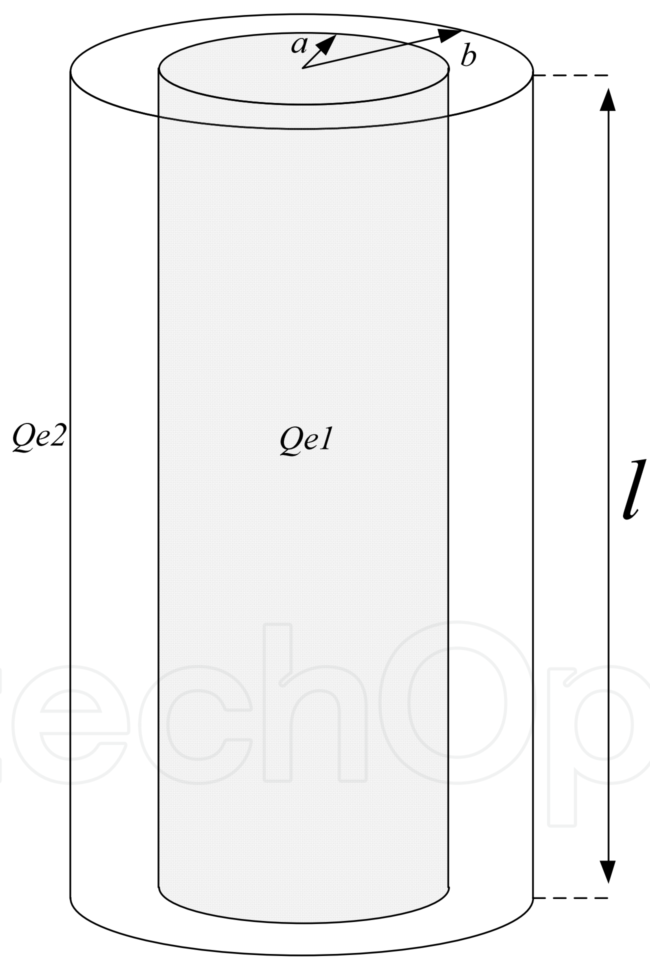


Figure 4.10 Geometrical approximation of the physical form of the cable.

$$C = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_r \cdot l}{\ln\left(b/a\right)} \quad \text{(F)} \tag{23}$$

$$C = \frac{\varepsilon_r}{17.97 \cdot \ln\left(b/a\right)} \quad (\mu\text{F/Km}) \tag{24}$$

Where: ε_r is the dielectric constant or relative permittivity of the insulating material between conductors, ε_o is the dielectric constant in the vacuum, l is the length of the conductor cylinders and (*a, b*) are the radius of conductor cylinders.

Finally, the cable has a leakage current from the conductor to ground (represented by a conductance G). The dielectric is a material with low conductivity, but not zero, i.e. the insulation presents high impedance, nevertheless, this does not mean infinite. Thus, the conductance G represents the current generated from the conductor to ground (the shield connected to ground) through the dielectric because the insulation is not ideal.

In short, transmission lines are basically circuits with distributed parameters, i.e. R, L, C and G are distributed along the whole length of line. Where:

- The distributed resistance R of the conductors is represented by a series resistor (expressed in ohms per unit length).
- The distributed inductance L (due to the magnetic field around the wires, self-inductance, etc.) is represented by a series inductor (henries per unit length).
- The capacitance C between the conductor and the shield is represented by a shunt capacitor C (farads per unit length).
- The conductance G of the dielectric material separating two conductors (the shield and the conductor) is represented by a conductance G, shunted between the signal wire and the return wire (Siemens per unit length).

Therefore, a transmission line can be represented electrically per phase for each differential length as in Figure 4.11 [47], [48] y [49].

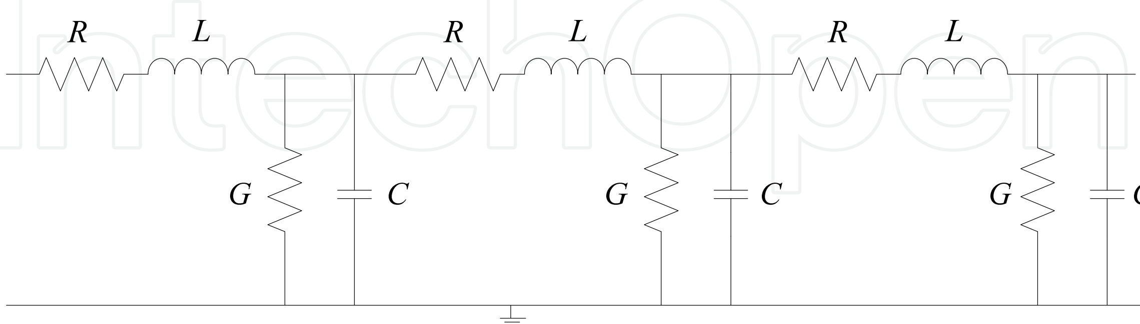


Figure 4.11 Electric representation of the cable per differential length.

In the same way, for three-phase transmission lines, the cable can be represented using three identical schemes per phase as follows, Figure 4.12.

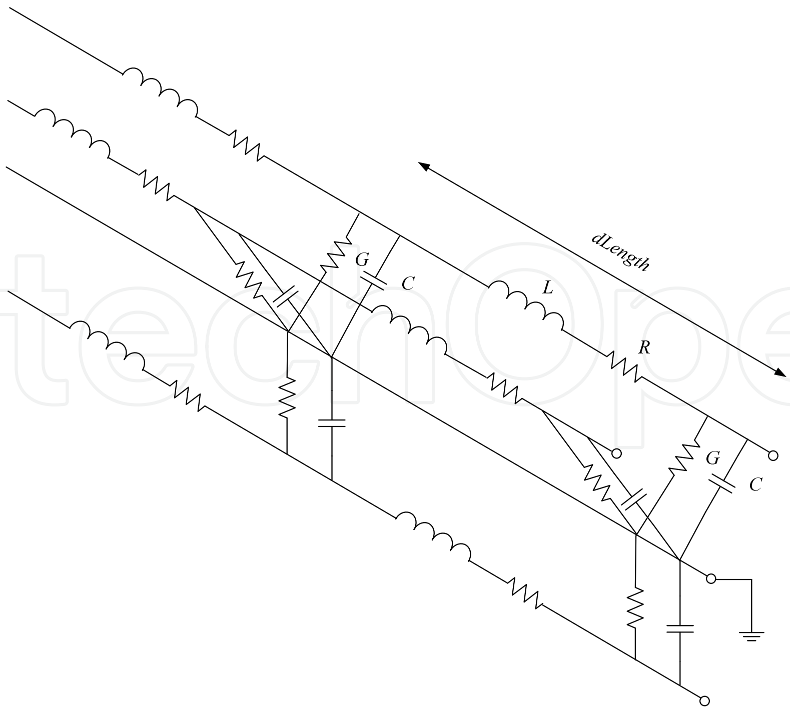


Figure 4.12 Electric representation of the three phase cable per differential length.

4.2.1.1 Skin effect

In DC circuits, the current density is similar in all the cross section of the conductor, but in AC circuits, the current density is greater near the outer surface of the conductor. This effect is called skin effect.

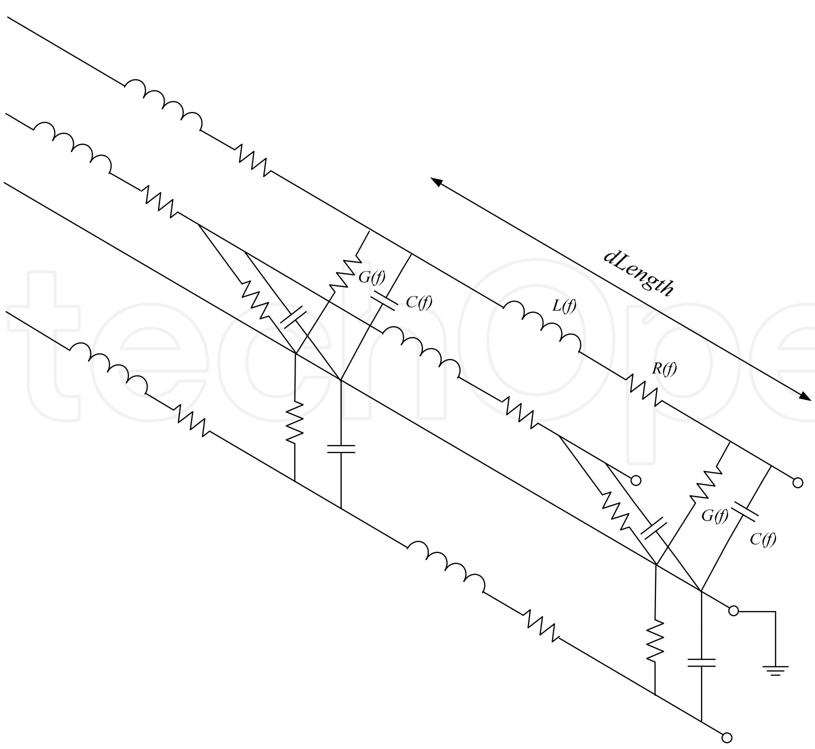


Figure 4.13 Electrical representation of a three-phase cable per differential length with frequency dependent parameters.

Due to this phenomenon, AC resistance of the conductor is greater than DC resistance. Near to the center of the conductor there are more lines of magnetic force than near the rim. This causes an increment in the inductance toward the center and the current tends to crowd toward the outer surface. So at high frequencies the effective cross section area of the conductor decreases and AC resistance increases.

In short, the skin effect causes a variation in the parameters of the cable, due to the non uniform distribution of the current through the cross section of the cable. This variation depends on frequency. Consequently, RGLC parameters are frequency dependent.

If this effect is taken into account the electric representation of the cable for each differential length is represented as shown in Figure 4.13.

4.2.2 Power transmission line modeling options

Based on the electric representation of the cables and depending on the cable model requirements, it is possible to perform more or less simplifications, in order to maintain the accuracy of the model and reduce its complexity. Thus, there are several ways for modeling a cable; these models can be classified as follows [50].

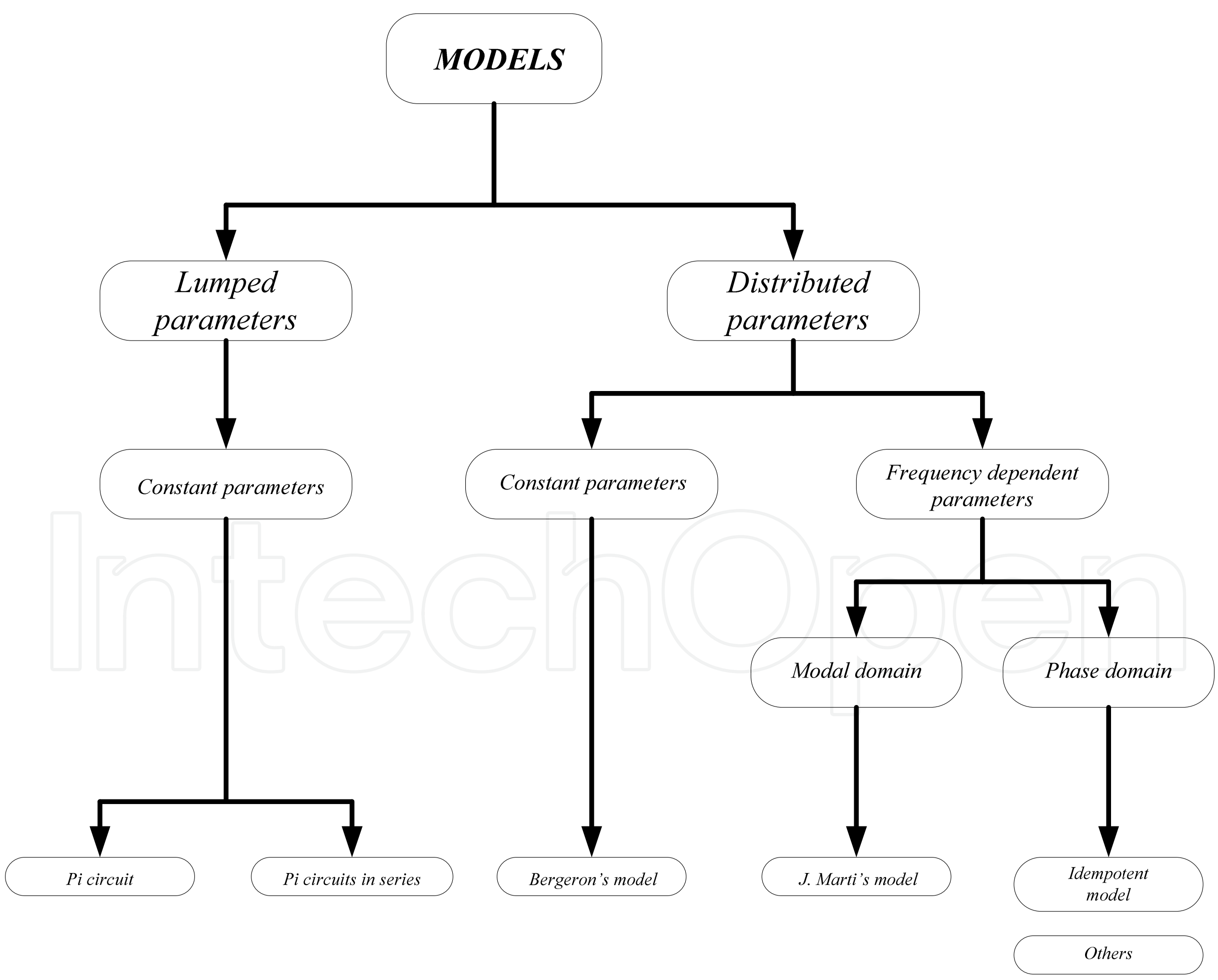


Figure 4.14 Classification of the different types of cable models.

In the present work, these models are divided into models based on constant parameters and models based on frequency dependent parameters. This division is made, because these two groups are based on different electrical representations, Figure 4.12 and Figure 4.13.

Thus, according to [51] for modeling the transmission lines with constant parameters there are the following options:

- Bergeron’s traveling wave.
- Standard short, medium and long line models for phasor domain. If only care about 50-60Hz.
- Sequence of single phase “π” segments. In order to model the transients in easy way.

If the objective is the analysis of a wide frequency spectrum accurately, a more accurate model of a line can be developed considering the RGLC parameters distributed and frequency dependent. So, in this report, the following frequency dependent cable models are considered:

- Frequency dependent model in modal domain (J. Marti).
- Frequency dependent model in phase domain (Idempotent model)

4.2.2.1 Constant parameter models

All the mathematical analysis of the evolution of the current and voltage to develop constant parameter models are based on a generic segment of the cable with length (Δx). Therefore, these models are developed starting from the electrical representation of Figure 4.11

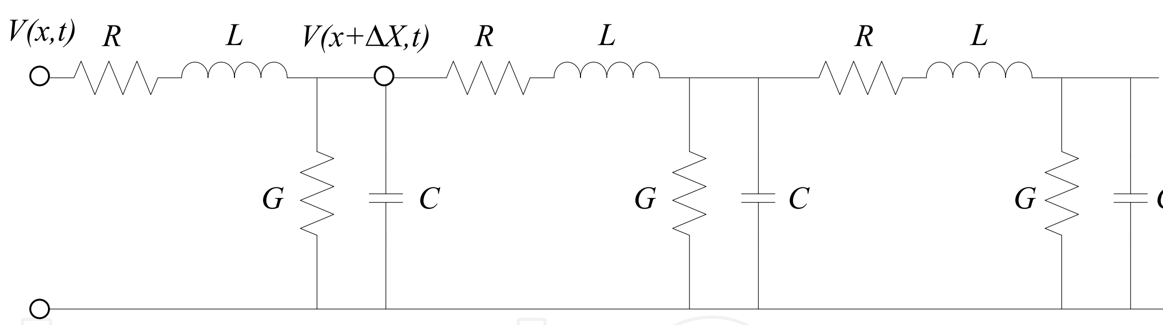


Figure 4.15 Electrical representation of a generic cable segment with constant parameters.

Where: *V(x,t) and V(x+*Δ*x,t)* are instantaneous voltages on x and $x+\Delta x$ respectively and I(x,t) and I($x+\Delta x,t$) instantaneous current on x and $x+\Delta x$.

Applying Kirchoff's laws to this circuit, it is possible to obtain the following equations to describe the behavior of the circuit:

$$V(x,t) - V(x+\Delta x,t) = \Delta V \tag{25}$$

$$\Delta V = -(RI(x,t) + L\frac{\partial I}{\partial t})\Delta x \tag{26}$$

$$I(x,t) - I(x+\Delta x,t) = \Delta I \tag{27}$$

Therefore, as can be seen at Figure 4.38, using the reactive power management which compensate the reactive power at both ends, the maximum current value decreases in comparison with the management way which injects the reactive power in one end only. As a result, the capability of the cable to carry active power increases. In the same way, the conduction losses are reduced.

Going more depth into the analysis, a more detailed comparison is carried out. In this second case, more cable lengths, different voltages and several transmitted active power levels are considered.

For that purpose, two cables are considered: the cables "A" and "B" of Table 4.4. As in the case before, there are modeled like several "π" circuits in series.

Based on these two cables, the total current along the line is obtained, for these two ways of the reactive management. In this case, two main scenarios are considered: 30 MW of transmitted active power with 36 kV of transmission voltage and 150 MW of transmitted active power with 150 kV of transmission voltage.

In each one of those scenarios, four cable lengths are considered: 50Km, 100Km, 150Km and 200Km. The results of the total current along the line for these configurations are depicted in Figure 4.39.

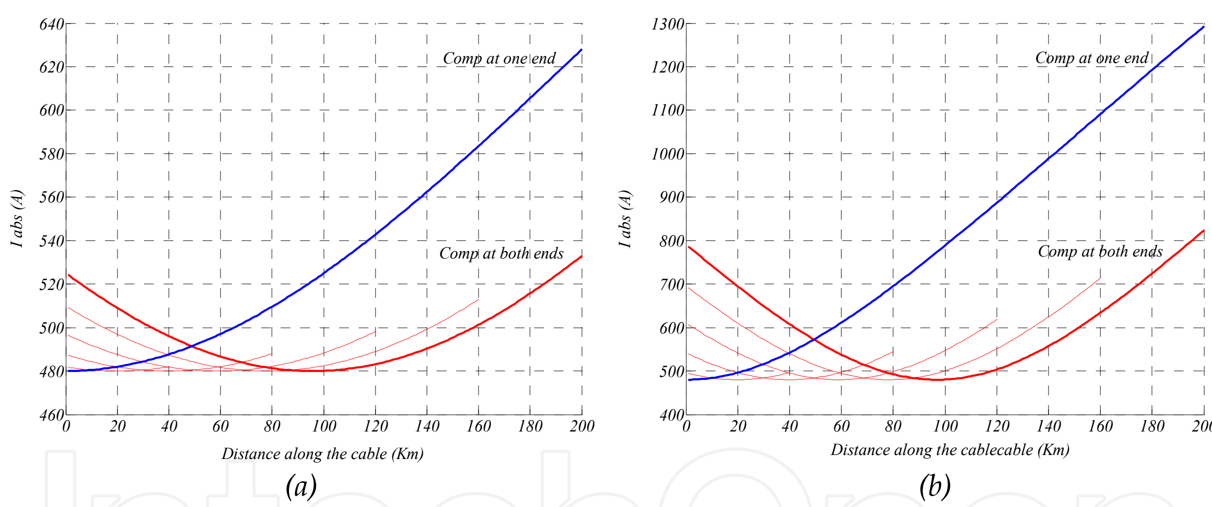


Figure 4.39 Total current along the submarine cable depending on cable length, compensation at both ends (red) and onshore compensation only (blue). (a) 30MW-36kV configuration and (b) 150MW-150kV.

Figure 4.39 shows the current along the cable for different lengths. For the case of the only onshore compensation, for different cable lengths, circulates the same current at the same length. On the contrary, with a compensation of 50% of the reactive power at each ends, the minimum current appears in the middle of the cable and the maximum currents at both ends.

This reduction and current distribution pattern along the cable happens for all the cable lengths and all the configurations. The different configurations and the different cable properties only affects on the amount of the generated reactive power, not in this maximum current reduction or in the shape of the current along the cable.

The management of the reactive power through the cable is determinant for long distances, because without the proper reactive power compensation, the cable may not be capable to transmit the required energy.

For example, the scenario with 150MW-150kV (using the cable "B" of Table 4.4) has a rated current of 1088A. But, as can be seen in Figure 4.39, for cable lengths longer than 150Km the required total current is bigger. Therefore, if a reactive power compensation at both ends is not performed, the cable cannot be capable to transmit the required active current.

4.3.2.2 Reactive power compensation: fixed or variable

Before to perform the analysis about the compensation characteristic fixed or variable, it is important to know how is generated the reactive power in the cable in more detail.

In addition to the capacitive component; the cable also has an inductive component. So, the reactive power generated in the cable is not constant at a specific voltage, depends on the transmitted power.

The capacitive reactive power generated in a specific cable (specific capacitive component) is determined by the applied voltage; due to this component is a "shunt" impedance. However, the inductive reactive power generated by the cable depends on the amount of active current flowing through the cable (transmitted active power), Figure 4.35. As a consequence, the amount of the reactive power generated by the cable varies.

$$Q_C = \frac{|V_C|^2}{|X_C|} \tag{98}$$

$$Q_L = |I_L|^2 \cdot |X_L| \tag{99}$$

Where: Q_C is the capacitive reactive power per phase, $|V_C|$ is the module of the voltage applied to the capacitive component, Q_L is the inductive reactive power per phase, $|I_L|$ is the module of the current through the inductive component, $|X_L|$ is the module of the inductive impedance and $|X_C|$ is the module of the capacitive impedance.

The philosophy of the reactive power management is the minimization of the total current flowing through the cable by reducing the reactive current flowing through the cable as much as possible.

Thus, to reduce to the minimum the reactive current flowing through the cable by the injection of the inductive current at both ends, it is necessary to inject exactly the half of the capacitive reactive current generated by the cable.

Therefore, because of the variation in the reactive current generated by the cable, the half of this reactive current needed for the optimum reactive power management varies too. This variation at each end is exactly the half of the total variation of the cable.

However, considering the total capacitive reactive current generated by the cable, this variation is quite little. So, the use of big inductances to perform the reactive power compensation is an economic option.

Regarding to the characteristics of those inductances, their inductivity depends on the reactive power generated by the submarine cable: The capacitive reactive power (equation (98)) minus the inductive reactive power (equation (99)), this last one, depending on the transmitted active power. So, the inductivity of those inductances has to be adjusted for a specific transmitted active power.

The best option, the option which reduces to the minimum the required maximum current of the cable, can be achieved adjusting the inductivity for the worst case. The case when the line is transmitting the rated active power. When the cable is transmitting the rated power, the maximum active current is flowing through the cable, so, if the reactive current flowing through the cable is optimized (reduced to the minimum) for this case, the required rated current of the cables is reduced.

The expression of the generated inductive reactive current / power at these inductances is shown in equations (100) and (101).

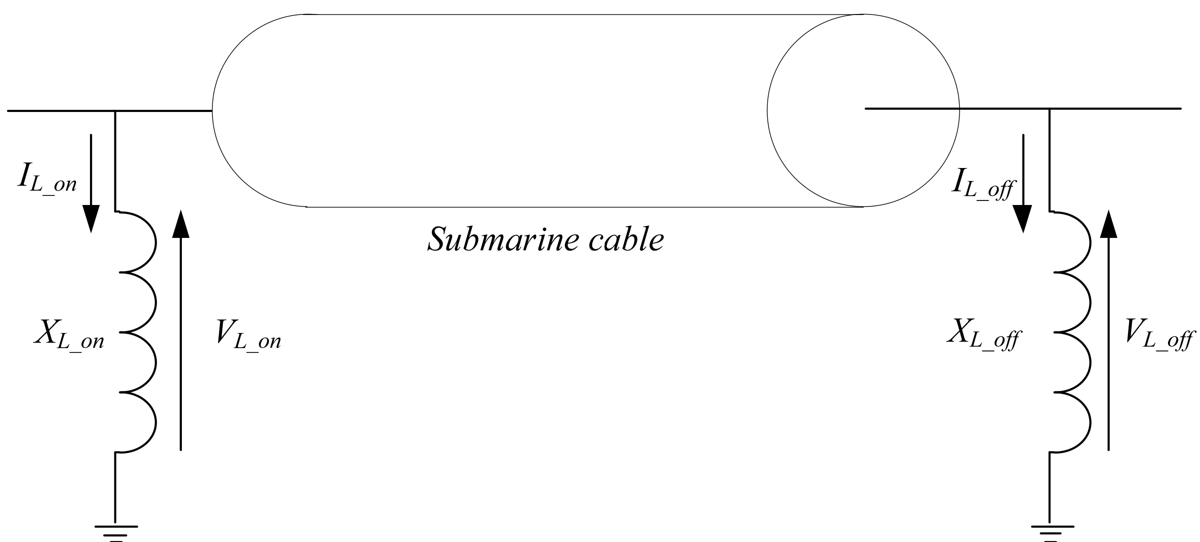


Figure 4.40 Graphic representation of a submarine cable (mono-phase) with inductances at both ends.

$$Q_{Lcomp\_on} = \frac{\left|V_{L\_on}\right|^2}{\left|X_{L\_on}\right|} = \frac{\left|V_{L\_on}\right|^2}{\omega \cdot L\_on} \tag{100}$$

$$L\_on = \frac{\left|V_{L\_on}\right|^2}{\omega \cdot Q_{Lcomp\_on}} \tag{101}$$

Where: Q_{Lcomp} is the module of the inductive reactive power and $|V_L|$ is the module of the applied voltage in the inductance.

4.3.3 Comparative of different types of reactive power compensation for a specific scenario in PSCAD

Any change in the power characteristics at the onshore substation, affects only to the circuit which is after this point, i.e. any change in the power factor at this point (PCC), only affects to the characteristics of the power injected in the main grid.

Nevertheless, controlling the power factor at the collector point of the offshore wind farm (the offshore end of the transmission cable), it is possible to control the active and reactive current relation through the transmission line. Due to the fact that this point is the energy "emitter" point. Thus, to carry out the management of the reactive power flowing through the transmission line, the main point to control the reactive power is the collector point.

Therefore, to perform the management of the reactive power flowing through the transmission line, there are three different options:

- Option 1: Without a reactive power management through the cable. The energy is generated with a unitary power factor in the wind farm, i.e. P.F. ≈1 in the "emitter" end of the cable and then transmitted through the submarine cables to the onshore substation. At this point, the reactive power generated in the cable is compensated to integrate the energy into the main grid.
- Option 2: With a rough reactive power management. The inductive reactive power is injected at both ends, but via inductances, always the same quantity for the same voltage.
- Option 3: With an adjusted reactive power management. The inductive reactive power is adjusted dynamically to obtain the same current module at both ends, i.e. the reactive power is injected depending on transmitted active power.

In the present section, a comparative of these three different options is carried out. For this purpose, a scenario using the cable model validated in the previous section is developed. This scenario has a 150 MW rated power, with a transmission voltage of 150 kV and 50 Km submarine cable length.

The objective is to obtain the main parameters of the transmission system upon this scenario for each one of those three management options. The parameters taken into account are: Active power losses, the reactive power generated in the transmission system and the voltage drop.

The analysis is focused exclusively in the transmission line and in the steady state, so, the wind farm is considered as a controlled P,Q source (see Figure 4.41).

The reactive power generated by the submarine cables varies with the amount of the transmitted active power, thus, a range of the transmitted active power is defined. This range is calculated, considering that the wind turbines generate energy with wind speeds between 3.5-30m/s. If the wind farm has 30 wind turbines of 5 MW, depending on the equation (102) explained in section 2.2.3, the range of the generated active power of a wind farm is approximately 5MW to 150 MW.

$$P_t(v) = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot V_{wind}^3 \cdot Cp \qquad (102)$$

Where: $P_t(v)$ is the output power depending on the wind in Watts, ρ is the density of air (1.225 measured in kg/m ^{3} at average atmospheric pressure at sea level at 15° C), r = the radius of the rotor measured in meters (63m), V_{wind} = the velocity of the wind measured in m/s and Cp = the power coefficient (0.44).

4.3.3.1 Option 1: Without reactive power management (reactive power compensation at one end)

In this first case, the first of the three considered reactive power management options is analyzed. To this end, the scenario illustrated in Figure 4.41 is simulated.

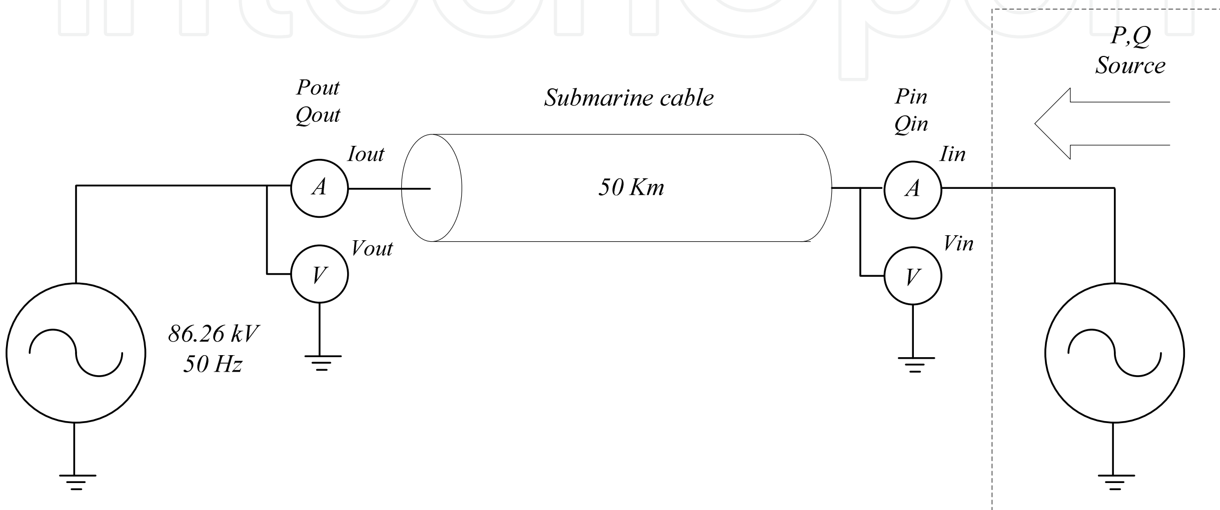


Figure 4.41 Diagram of the first simulation scenario, submarine cable without reactive power management.

In Table 4.6, the simulation results of the transmission system depicted in Figure 4.41 are summarized. These results are obtained in the active power range of the offshore wind farm (5-150MW).

Pin *MW (FP=1)*	**Generated *Q*** *(Qout-Qin)*	***P* losses** *(Pin-Pout)*	**ΔV (kV)** *(Vout-Vin)*	*Iin*	*Iout*
5	83.07 MVAR	0.237 MW	1.22	21 A	318 A
15	83.07 MVAR	0.251 MW	1.31	58 A	323 A
25	83.05 MVAR	0.284 MW	1.425	99 A	333 A
40	82.9 MVAR	0.344 MW	1.5	153 A	357 A
60	82.55 MVAR	0.488 MW	1.7	234 A	392 A
80	82.01 MVAR	0.683 MW	1.87	312 A	440 A
100	81.32 MVAR	0.915 MW	2.03	385 A	495 A
120	80.4 MVAR	1.22 MW	2.18	459 A	555 A
150	78.75 MVAR	1.76 MW	2.38	575 A	648 A

Table 4.6 Simulation results for the first scenario. Reactive power generated in the cable, active power losses and voltage drop.

As can be seen in Table 4.6, the capacitive reactive power generated in the transmission line is about 83 MVAR. This value is in concordance with the estimation in a simply way of the equation (103) explained in section 4.3.2.2.

$$Q_C = 3 \cdot \frac{|V_C|^2}{|X_C|} = \frac{86.6^2}{273.22} = 82.3MVAR \qquad (103)$$

Where: Q_C is the capacitive reactive power for the three phases, $|V_C|$ is the module of the applied voltage to the capacitive component and $|X_C|$ is the module of the capacitive impedance.

4.3.3.2 Option 2: Transmission system with fixed reactive power compensation (at both ends)

In the second case, the management of the reactive power flowing through the transmission line is made via inductive impedances at both ends of the line, (Figure 4.42). The value of the inductance is calculated to compensate exactly the reactive power generated in the cable when this is carrying the rated active power, equations (100) and (101).

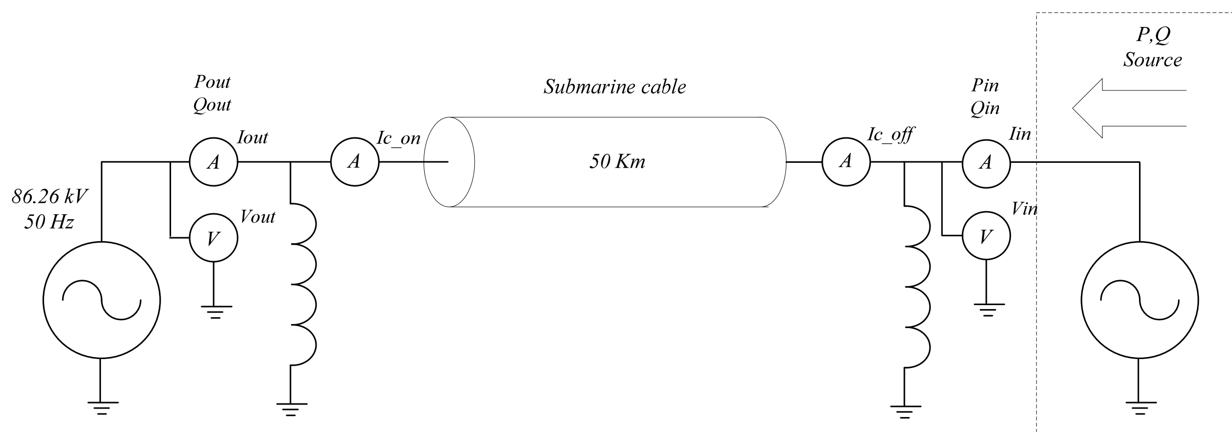


Figure 4.42 Diagram of the second simulation scenario, submarine cable with fixed inductances at both ends.

The results, obtained by the simulation of the defined scenario with the second option for the reactive power management, are depicted in Table 4.7.

Comparing the results in Table 4.6 with the results on Table 4.7, can be seen how the reactive power management reduces significantly the voltage drop in the line. In the same way, with this kind of reactive power management, the active power losses have an important decrement. Especially, in cases when the transmitted active power through the line is less than the 50% of the rated power.

In the considered range of the active power generated for the offshore wind farm (5-150MW), the variation of the reactive power generated in the line is about 4.8 MVAR, i.e. the submarine cables in combination with the inductances have a 4.8 MVAR variation. This value is significantly low in comparison with the reactive power generated in the submarine cables 83 MVAR, approximately the 5%.

Pin *MW* *(FP=1)*	**Generated *Q*** *(Qout-Qin)*	***P* losses** *(Pin-Pout)*	**ΔV (kV)** *(Vout-Vin)*	*Iin*	*Ic_off*	*Ic_on*	*Iout*
5	4.92 MVAR	0.12 MW	0.106	17 A	151 A	171 A	26 A
15	4.88 MVAR	0.13 MW	0.19	55 A	162 A	174 A	60 A
25	4.8 MVAR	0.16 MW	0.27	95 A	178 A	193 A	99 A
40	4.58 MVAR	0.22 MW	0.41	151 A	217 A	230 A	153 A
60	4.12 MVAR	0.365 MW	0.596	234 A	274 A	280 A	238 A
80	3.46 MVAR	0.56 MW	0.75	310 A	342 A	351 A	314 A
100	2.67 MVAR	0.79 MW	0.89	380 A	411 A	416 A	382 A
120	1.66 MVAR	1.1 MW	1.03	458 A	482 A	485 A	460 A
150	0.16 MVAR	1.65 MW	1.24	572 A	590 A	591 A	572 A

Table 4.7 Simulation results for the second scenario. Reactive power generated in the transmission system (cable + inductances), active power losses and voltage drop.

This value, the reactive power variation of the cables depending on the transmitted power, is in concordance with the estimation in a simply way of the equation (104) explained in section 4.3.2.2.

$$Q_L = 3 \cdot I_L{}^2 \cdot \left| X_L \right| = 3 \cdot 577^2 \cdot 5.246 = 5.23MVAR \tag{104}$$

$$I_L = \frac{P}{3 \cdot V_{\phi n}} = \frac{150MW}{3 \cdot 86.6kV} = 577A \tag{105}$$

Where: Q_L is the inductive reactive power for the three phases, $|I_L|$ is the module of the current through the inductive component, $|X_L|$ is the module of the inductive impedance, P is the transmitted power through the transmission line and $V_{\phi n}$ is the rated voltage per phase of the transmission system.

4.3.3.3 Option 3: Transmission system with variable reactive power compensation (at both ends)

In the third and last case, to achieve the optimum reactive power management, the inductive reactive current is injected at both ends of the cable depending on the transmitted amount of the active power.

As is estimated in the case before, the variation of the reactive power generated in the line (cable + inductances) is about the 5%. So, in this third case, the effect of this variation in the transmission system parameters is analyzed. For this purpose, the simulation of the scenario shows in Figure 4.43 is carried out.

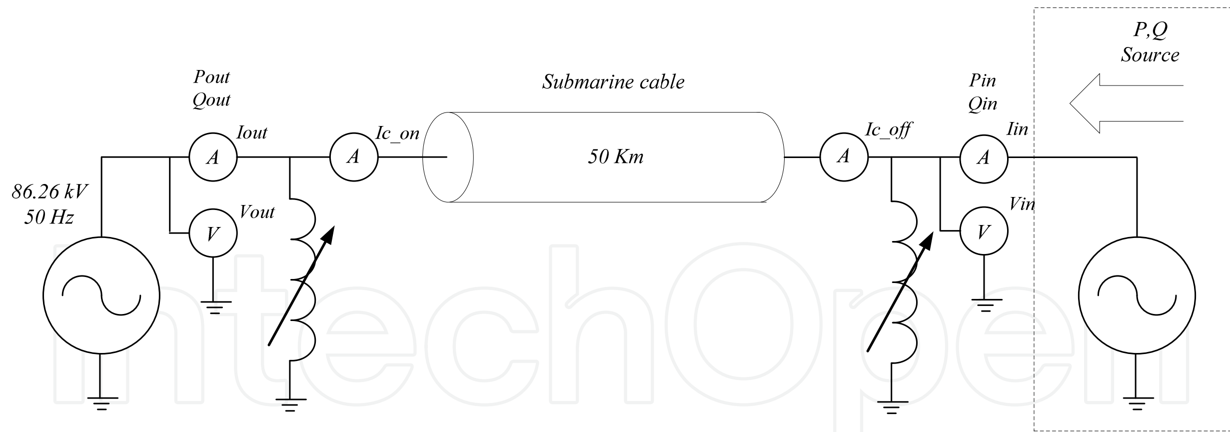


Figure 4.43 Diagram of the third simulation scenario, submarine cable with the injection of the inductive reactive power at both ends depending on the requirements.

The simulation results of the defined scenario (Figure 4.43), for the considered active power range of the offshore wind farm (5-150MW) are summarized in Table 4.8. Notice that in the results of Table 4.8, there are not shown the results of the reactive power generated in the transmission line, because the reactive power of the cable is totally compensated at both ends.

Pin *MW (FP=1)*	***P* losses** *(Pin-Pout)*	**ΔV (kV)** *(Vout-Vin)*	*Iin= Iout*	*Ic_on= Ic_off*
5	0.118 MW	0.035	17 A	160 A
15	0.13 MW	0.12	55 A	167 A
25	0.16 MW	0.2	95 A	185 A
40	0.22 MW	0.345	151 A	223 A
60	0.36 MW	0.536	234 A	277 A
80	0.56 MW	0.7	310 A	347 A
100	0.79 MW	0.855	380 A	413 A
120	1.1 MW	1.01	458 A	483 A
150	1.65 MW	1.24	572 A	590 A

Table 4.8 Simulation results for the second scenario. Active power losses and voltage drop.

Comparing the results on Table 4.8, with the results on Table 4.7, it can be seen how the active power losses have not a significantly reduction. With regards to the voltage drop, this has a little reduction only in cases when the transmitted active power through the line is less than the 50% of the rated power.

The fixed inductances at both ends of the cable are fit to achieve the optimum reactive power management with rated active power. So, in cases when the transmitted active power is close to the rated power, with both ways: with fixed inductances and with variable injection of the reactive power, similar results are obtained.

4.3.3.4 The effect of the cable length

The reactive power generated in the submarine cables depends on the cable length (Table 4.5), thus, as the length affects to the amount of reactive power to compensate, this aspect has to be analyzed.

In this way, with the increase of the reactive current through the line, the current limit of the cable (1088A in the present case, Table 4.4) has to be taken into account. If the required active current to transmit the rated power of the wind farm is close to the rated current of the cable or the transmission cable is too long, it is possible that without the proper compensation, the cable would not be capable to transmit the required power.

In Table 4.9, the results of the three types of reactive power management (explained in the previous sections) for two cable lengths 50 Km and 150Km are summarized.

Transmitted active power *MW (P.F.=1)*		***50 Km cable length***			
		ΔQ (MVAR)	*ΔP (MW)*	*ΔV (kV)*	*Imax (A)*
5 MW	*Option 1*	83.07	0.237	1.22	318
	Option 2	4.92	0.12	0.106	169
	Option 3	-	0.118	0.035	160
150 MW	*Option 1*	78.75	1.76	2.38	648
	Option 2	-	1.65	1.24	592
	Option 3	-	1.65	1.24	592
		150 Km cable length			
		ΔQ (MVAR)	*ΔP (MW)*	*ΔV (kV)*	*Imax (A)*
5 MW	*Option 1*	262.4	4.73	11.47	1012
	Option 2	11.9	1.05	0.61	504
	Option 3	-	1	0.075	482
150 MW	*Option 1*	256.9	8.4	14.6	**1130**
	Option 2	-	5.1	3.4	728
	Option 3	-	5.1	3.4	728

Table 4.9 Simulation results for different kind of reactive power management, for two cable lengths 50Km and 150Km.

Notice that without the proper reactive power management, it is impossible to transmit the rated power with the selected cable to 150Km away, because the required current for that purpose is higher than the current limit of the cable.

For cases with a submarine cables of 150Km or longer, providing the transmission system with reactive power management, it is possible to see a higher reduction in the voltage drop and active power losses. Making clear that, the more is the reactive power generated in the cable, the more important is a correct reactive power management.

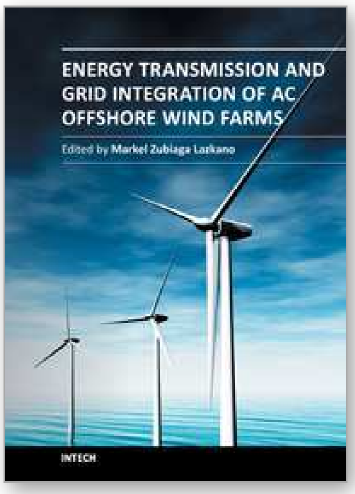
4.4 Chapter conclusions

In this chapter, the main characteristics of the submarine cables are analyzed, such as: their physical structure, the way to represent them electrically or different ways to model it, from the most simply to more complex models. Then, based on a validated cable model several electric aspects of the transmission lines are evaluated.

In this way, from the analysis carried out in this chapter is clear that the transmission of the 150 MW at 150kV to 50Km away is perfectly possible. At least if it is performed with the cable considered in this chapter. Using this cable, the voltage drop of the transmission line is less than 5% and the active power losses are not too high. In the same way, the current limit of the cable is enough to carry the rated active power at any circumstance. So, this scenario is perfectly valid and feasible.

The reactive power management of the submarine cable reduces significantly the active power losses and the voltage drop. This reduction is more obvious, in cases where the transmitted active power is less than the 50% and for long submarine cables (big amount of generated reactive power), i.e. this reduction is more obvious, in cases when the reactive current is high in relation to the active current.

The reactive power management, based on fixed inductances at both ends of the line has similar improvements in comparison with the variable compensation at both ends. Moreover, if those inductances are adjusted for the worst case, using fixed inductances, the maximum voltage drop, the maximum active power losses and the required maximum current for the cable are exactly the same. So, this option is simply and enough for a good reactive power management.



Energy Transmission and Grid Integration of AC Offshore Wind Farms
Edited by MSc Markel Zubiaga

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This book analyses the key issues of the offshore wind farm's energy transmission and grid integration infrastructure. But, for this purpose, there are not evaluated all the electric configurations. In the present book is deeply evaluated a representative case. This representative case is built starting from three generic characteristics of an offshore wind farm: the rated power, the distance to shore and the average wind speed of the location. Thus, after a brief description of concepts related to wind power and several subsea cable modeling options, an offshore wind farm is modeled and its parameters defined to use as a base case. Upon this base case, several analyses of the key aspects of the connection infrastructure are performed. The first aspect to analyze is the management of the reactive power flowing through the submarine cable. Then, the undesired harmonic amplifications in the offshore wind farms due to the resonances and after this, transient over-voltage problems in the electric infrastructure are characterized. Finally, an offshore wind farm connection infrastructure is proposed in order to achieve the grid code requirements for a specific system operator, but not as a close solution, as a result of a methodology based on analyses and simulations to define the most suitable layout depending on the size and location of each offshore wind farm.